SURF Research Proposal Form

**This proposal form is for all students applying to: SURF L&S, SURF Rose Hills Independent, or SURF Rose Hills Experience. This is NOT the correct application form for the Math Team fellowships.

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Instructions: The SURF proposal has 5 sections. Each section specifies how long your response should be (approximate word number). Please keep your responses single space and use 12pt font. While it is useful and appropriate to use technical language in parts of your proposal (terms specific to your discipline), you should aim to have your proposal understandable to a more general academic audience. Avoid jargon or overly abstract phrasings. Type or paste in your responses to the 5 prompts below.

When you are finished, save the document as a PDF with a filename in this format: ***ProposalYourLastName.pdf (example: ProposalSmith.pdf)*** You will be asked to upload this completed PDF research proposal form when you submit your application online.

1. Research Statement: 150-200 words. What specific question will you pursue with your research and why is it important to the field? This section enables you to give the reviewers an overview of your project. Keep in mind that other sections give you an opportunity to develop more details around the background, methodology, and rationale for the project.

My research will investigate the lower-dimensional behavior of the ‘anomalous’ properties of a certain, recently proposed, Lagrangian in 6-dimensional quantum field theory. Over the past century, quantum field theory (QFT) -- a framework describing subatomic particles as excitations of fundamental ‘fields’ -- has predicted incredibly accurate physical measurements, yet it remains a topic riddled with open problems tackled by theoretical physicists today. Interacting QFTs in higher dimensions (particularly 6d) is one such open problem, motivated by string theory, a highly theoretical mathematical model attempting to describe all of nature. These interacting QFTs have ‘Lagrangians’ (precursors to ‘equations of motion’) that can describe ‘M5-branes,’ which are objects of fundamental interest in string theory. However, attempts to write a Lagrangian for these theories are susceptible to quantum ‘anomalies’, which are red flags indicating that a symmetry of classical physics is incompatible with quantum mechanics. Analysis of the behavior of these anomalies, and the quantum interactions they induce in the corresponding theory, can be probed by looking at their consequences in lower dimensions on special shapes. My project will explore new consequences of these interactions in lower dimensions, once the extra dimensions are turned into (‘compactified’ into) a circle and an orbifold (cone).

2. Background to the Topic and Rationale for Your Research: 300-400 words. What is already known about the field of research you will be working on? How does your research project fit in with what is being done currently in the field, and how does it build upon knowledge on the topic or fill in gaps in the field? Please cite references from the literature when applicable; these citations should be listed in #5 of this proposal.

My project addresses 6d (2,0)-theory, which is a 6-dimensional type of quantum field theory (QFT), predicted by arguments in string theory [2, 3]. On the one hand, QFT, which describes subatomic particles and their interactions in the language of underlying ‘fields,’ has long been established as the de facto framework adopted by nearly all particle physicists today (as well as a growing number of condensed matter physicists, cosmologists, and mathematicians). On the other hand, many ideas in QFT remain enigmatic, especially with the advent of string theory, an extension of QFT that attempts to provide a self-contained mathematical model completely describing all of nature. Among such mysterious subtopics in QFT is the idea of 6d (2,0)-theory, which would provide insight into the behavior of M5-branes -- fundamental (and still poorly understood) objects in string theory akin to generalized ‘points’ in higher dimensions [2, 4]. Additional motivation for studying 6d (2,0)-theory includes applications in pure mathematics, particularly knot theory [5, 6, 7], as well as condensed matter physics [8].

One of the many glaring gaps in 6d (2,0)-theory is describing it with a proper ‘Lagrangian,’ which is the modern mathematical abstraction in which physicists extract the ‘equations of motion’ describing a theory. A recent proposal in [1] suggests one such Lagrangian for a variant of the 6d (2,0)-theory, where an M5-brane is subjected to strong magnetic-like flux. However, the Lagrangian that [1] provides must be modified because it has a quantum ‘anomaly,’ which is defined as the manifestation that a fundamental symmetry (an ‘action’ on a system that leaves it ‘the same’) of classical physics is not translated well into the language of quantum physics and the subatomic world [9, 10, 11]. Although the anomaly is a signal that the proposed Lagrangian and corresponding theory is incomplete, calculations performed on the quantum interactions they induce can tell us much about the anomaly’s behavior, which would reveal more about the structure of M5-branes. These (novel) quantum interactions can exhibit revealing behavior in lower dimensions via a process called ‘compactification,’ which is the ‘reduction’ of dimensions to a specific shape. Although compactification techniques are well known [14, 15], what would be novel is to compactify the specific quantum interactions suggested by the 6d theory in [1], which would reveal much about its anomalous properties. This will be the focus of my research project.

3. Research Plan - Methodologies and Timeline: 450-700 words. Please define the main challenges of your project and what research methods you will use to address these challenges. Describe your research plan for the summer in chronological order - either use a week-by-week timeline or phases approach (i.e. week 1, week 2…or phase 1, phase 2…). Each week/phase should specify goals, action items, and methods. Please include in your plan information about exactly how/when you will check in with your research mentor.

Broadly, the challenges of my project are as follows: First, understand the developments in the field and the abstract mathematical formalism leading up to the problem. The next steps are simple in principle, but complicated in practice: check and calculate the anomaly in [1] to deduce the induced quantum interactions of the theory, compactify them to lower dimensions, and analyze the behavior there. My research mentor and I will check in by meeting ~3 times a week and discussing my progress.

Phase 1: (Literature on anomalies and 6d QFT) (~2 weeks)
The first phase will be familiarizing myself with past/current literature regarding quantum anomalies and how they appear in 6d (2,0) quantum field theories. I will particularly study the theory proposed by Ganor in [1] (M5-brane in strong flux), and the methods of compactification [14, 15]. This work will consist of literature search, studying papers, and discussions with my mentor, with emphasis on the 'Lagrangians' proposed, the anomaly, and techniques of compactification. This first phase will be essential to understanding the calculations conducted in the rest of the project.

Phase 2: (Check and calculate the anomaly of [1]) (~1 week)
Next, I will begin checking the anomaly present in [1]. This will primarily consist of computational techniques in Mathematica/Python to run certain equations and operations on terms in [1], and check, using literature from Phase 1, where and how exactly the anomaly in [1] arises. This is essential, since, for example, knowing which specific pieces of the equations proposed by [1] are responsible for the anomaly would give insight into the anomaly's implications. Various approaches will be taken to understand the implications of the anomaly; for example, one way is to use my computations to observe if the anomaly induces novel terms in the Lagrangian, which would imply new types of quantum interactions in the theory. This would be essential to understand before I undertake the process of compactification.

Phase 3: (Compactification to a circle) (~2-3 weeks)
In phase 3, I will begin the compactification process, whereby I will take the interactions of the 6d theory of [1] and analyze their behavior in lower dimensions. First, we will compactify a dimension to the simplest shape -- a

circle. Through this process, we reduce the 6d theory to a 5d one, and the output might be intriguing new interaction terms in 5d that haven't been examined before, potentially offering insight regarding the consequences of the terms in the original 6d theory induced by the anomaly. Again, Mathematica/Python will be used extensively to carry out operations on the complicated terms.

Phase 4: (Compactification to an orbifold (cone) and consolidating calculations) (~2-3 weeks)

After examining the behavior of the interactions when we undertake compactification to a circle, I will next attempt the compactification to an orbifold (cone), which is interesting since the 'tip' of the cone would carry additional degrees of freedom that may imply new behavior of our compactified 6d theory. For example, new types of particles could be implied by compactification to a cone at its tip, which would tell us much about our original 6d theory and its interactions induced by the anomaly. In the end, I will consolidate all previous calculations, and finally deduce from my compactification processes information about the behavior of quantum interactions suggested by the anomaly in [1]. This would reveal new behavior about the anomaly itself, and help to more precisely characterize theories, such as that in [1], which have anomalies. In turn, this would help advance the literature and knowledge of 6d QFTs and how they can be used to describe M5-brane behavior. Discussing my final discoveries with my mentor will be the focus of this phase. If time allows, other types of 6d theories can be explored similarly, as in [12, 13].

4. Your Qualifications and Project Affiliations: 150-250 words. What experiences have prepared you to carry out this research project, including coursework, previous research experiences, and other relevant skill building? If your project involves access to people and/or institutions to support your work (i.e. interviewing subjects or partnering with institutions), please describe the affiliations, permissions and agreements you have already established as part of your plan.

My project inherently involves advanced topics in theoretical physics. As such, my previous and current coursework in graduate-level Quantum Field Theory, graduate level mathematics, and the canonical undergraduate physics and mathematics curriculum (which I will have completed before this summer) will be essential in preparing me for this research and understanding the abstract foundations on which the topics are built. Furthermore, my previous years of research experiences in both theoretical cosmology and experimental particle physics have wisened me with the skills of literature review/searching and exposure to open problems in high-energy physics, respectively, as well as general proficiency in computational techniques (Python, Mathematica, C++, etc.) in physics, which are necessary for the calculations needed in this project. These experiences have additionally acclimated me to research culture and taught me crucial soft-skills such as group collaboration, effective communication, time management, and overcoming roadblocks and personal frustrations, which will be essential when tackling particularly abstract topics such as those in my proposed project. In addition, I am working with my faculty sponsor this spring semester, where we are currently meeting and discussing the theory and literature behind the topics in my proposed project. This head-start in familiarity with the ideas in my project will directly prepare me well for the actual execution of the project in the summer.

5. Citations and Core Texts: No longer than 1 page. This section should contain citations for any references you made in your proposal, and you are welcome to list any additional texts that you feel are central to your project.

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5. Khovanov, M. (1999). A categorification of the Jones polynomial. arXiv preprint math/9908171.
6. Witten, E. (2009). Geometric Langlands from six dimensions. arXiv preprint arXiv:0905.2720.
7. Witten, Edward (2012). "Fivebranes and knots". Quantum Topology. 3 (1): 1–137. doi:10.4171/qt/26.
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9. 't Hooft, G. (1980). "Naturalness, Chiral Symmetry, and Spontaneous Chiral Symmetry Breaking". In 't Hooft, G. (ed.). Recent Developments in Gauge Theories. Plenum Press. ISBN 978-0-306-40479-5.
10. Adler, S. L. (1969). "Axial-Vector Vertex in Spinor Electrodynamics". Physical Review. 177 (5): 2426–2438. Bibcode:1969PhRv..177.2426A. doi:10.1103/PhysRev.177.2426.
11. W. A. Bardeen (1969) Physical Review vol 184 p. 1848.
12. Kallosh, R., & Sorokin, D. (2005). Dirac action on M5 and M2 branes with bulk fluxes. Journal of High Energy Physics, 2005(05), 005.
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14. Green, M., Schwarz, J., & Witten, E. (2012). Superstring Theory: 25th

Anniversary Edition (Cambridge Monographs on Mathematical Physics). Cambridge: Cambridge University Press. doi:10.1017/CBO9781139248563
15. Polchinski, J. (1998). String Theory (Cambridge Monographs on Mathematical Physics). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511816079